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Atmospheric Refraction Error and Its Compensation for Passive Optical Sensors

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4 June 1984

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

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ATMOSPHERIC REFRACTION ERROR AND ITS COMPENSATION FOR PASSIVE OPTICAL SENSORS

K-P. DUNN

Group 32

TECHNICAL REPORT 686

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ABSTRACT

A wide range of passive optical sensor applications often require the sensor to operate within the atmosphere while the objects it examines are outside the atmosphere. The refraction of light by the earth's atmosphere becomes a significant error source when the objects are at low elevation angle. When the measurement accuracy at low elevation angle is important for the sensor application, an accurate refraction compensation scheme is needed. In this report, we provide an algorithm that will compensate the error when the object is at a finite range from the sensor. Sensitivities of compensation errors to object range error, atmospheric model mismatch, and possible statistical variations about a given atmospheric model are also provided.

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I. INTRODUCTION

The refraction of light by the earth's atmosphere has been observed by astronomers for centuries. In order to obtain the actual star location, one needs to know the path of the light ray from the star through the atmosphere. Mathematical formulas that trace a light ray through nonuniform medium have been derived and can be used for this purpose.[1]-[2] With limited atmospheric data around the earth, it was impossible to compensate the bending of light accurately. Until recently, numerous data have been collected around the earth in different seasons and at different altitudes. Atmospheric models have been generated and used to correct these errors, for example six atmosphere models are provided in a computer code for atmospheric transmittence and radiance computation called LOWTRAN 5.[3]

A wide range of passive optical sensor applications often require the sensor operate within the atmosphere while the objects it examines are outside the atmosphere. When the measurement accuracy at low elevation angle is important for the sensor application, an accurate refraction compensation scheme is needed. There are computer codes, for example LOWTRAN 5[3], which can be used to calculate the refraction error and compensate it. It is, however, not applicable to the case when an object is at a finite range from the sensor.

Figure 1.1 shows that for each true target position, the apparant elevation angle can be determined uniquely. However, given the apparent elevation angle, the true target elevation is determined only if the range to the target is known. This is the purpose of this report to provide an algorithm that will generate the actual refraction error for objects with finite range and also provide some sensitivites of these errors to the object range, the underlying atmospheric model and possible statistical variations about a given atmospheric model.

The report is organized in five sections. Section 2 provides a brief review of Fermat's principle and derives an important formula for ray tracing in spherical coordinates. In Section 3, a specific form of refractive index (a ratio of velocity of light in vacuum and in a medium) is assumed, namely, it is a spherically symmetric function about the center of the earth. The formula that computes the refraction error is derived for an object with a range R from the observer. A simplified version of Edlen's expression for the refractive index of air [4] is used in Section 4 to generate the refractive index of air at different altitudes from atmospheric profiles provided by LOWTRAN 5. The sensitivities of compensated elevation refraction errors to the object range, atmospheric model mismatches and the statistical varia-

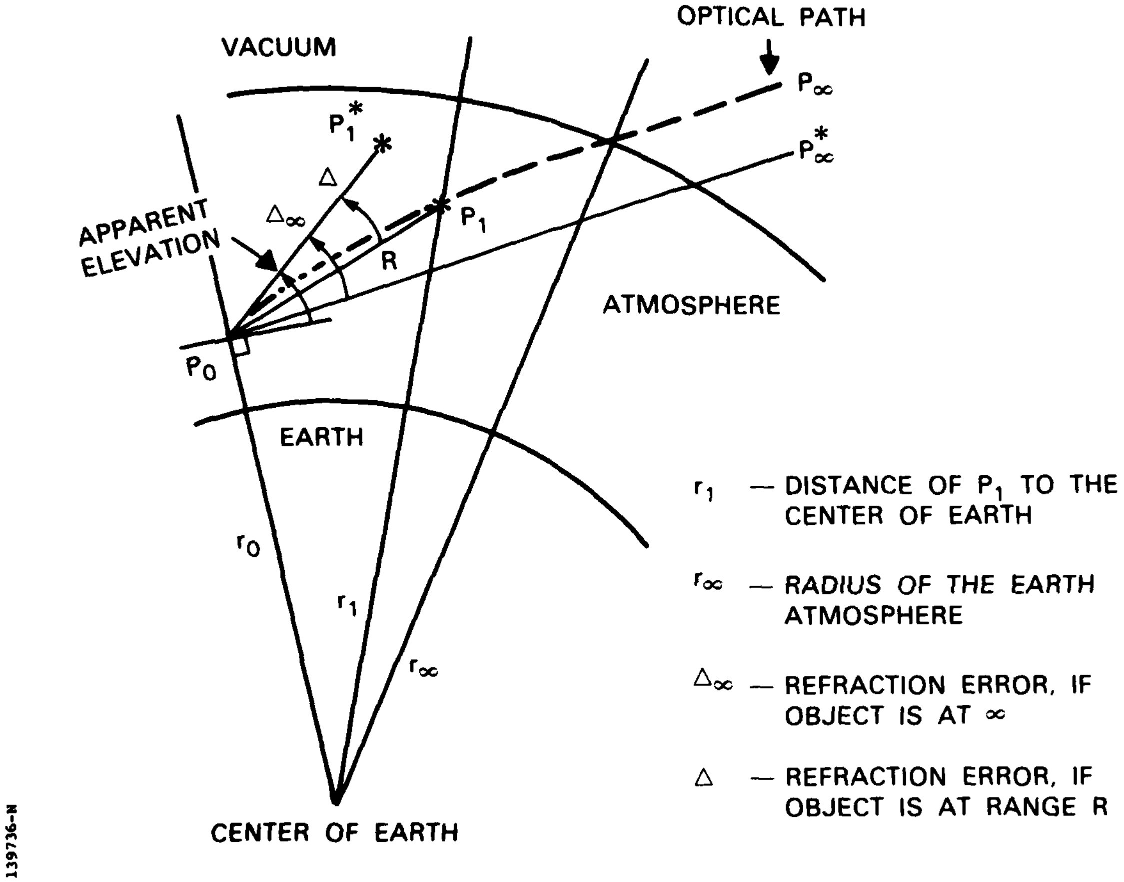


Fig. 1.1 For a given apparent elevation angle, the true elevation angle and hence the refraction error is a function of the target range R.

tions about a given model atmosphere are presented. A summary and conclusion is given in Section 5.

II. RAY TRACING IN SPHERICAL COORDINATES

When light rays are propagated through an atmospheric medium of continuously varying refractive index, they experience a change in direction or refractive bending. In this section, we will derive the equations for ray tracing in spherical coordinates from Fermat's principle.

2.1 Fermat's Principle[1]

Let n be the refractive index of a light ray in a medium. The optical length of a ray which joins points P_1 and P_2 (denoted by $[P_1P_2]$) is given by

$$[P_1P_2] = \int_{P_1}^{P_2} n \, ds \tag{2.1}$$

where s is the distance measured along the light ray.

Fermat's principle states that a light ray always chooses a trajectory that minimizes the optical length. In mathematical terms, Fermat's principle assumes the form,

$$[P_1P_2] = \int_{P_1}^{P_2} n \, ds = \text{minimum.} \tag{2.2}$$

Instead of the optical length, we can introduce the concept of transit time by dividing (2.2) by the constant c, the velocity of light in vacuum. Since the velocity of light in a medium with refractive index n is c/n, we have

$$[P_1P_2] = c\int_{P_1}^{P_2} dt. \tag{2.3}$$

Therefore, Fermat's principle is also known as the principle of least time.

2.2 The Euler Equations in Spherical Coordinates

Let us consider that the refractive index is a smooth and continuous function of position in spherical coordinates and is denoted by $n(r,\theta,\phi)$. We use the definition of the line element

$$ds = \sqrt{dr^2} = \sqrt{r^2 d\theta^2 + r^2\sin^2\theta d\phi^2}$$

$$= \sqrt{1 + r^2\theta'^2 + r^2\sin^2\theta\phi'^2}\ dr \tag{2.4}$$

with

$$\theta' = \frac{d\theta}{dr} \ ; \quad \phi' = \frac{d\phi}{dr} \tag{2.5}$$

to express (2.1) in the form

$$\int_{P_1}^{P_2} L(r,\theta,\phi,\theta',\phi')dr = \text{minimum}. \tag{2.6}$$

The function L is given by

$$L(r,\theta,\phi,\theta',\phi') = n(r,\theta,\phi)\sqrt{1 + r^2\theta'^2 + r^2\sin^2\theta\phi'^2} \tag{2.7}$$

In variational calculus, the function L in (2.6) is called the

Lagrangian. The solution of (2.6) is well known and can be obtained by solving the Euler equations:

$$\frac{d}{dr}\ \frac{\partial L}{\partial \theta'} - \frac{\partial L}{\partial \phi} = 0, \tag{2.8}$$

$$\frac{d}{dr}\ \frac{\partial L}{\partial \phi'} - \frac{\partial L}{\partial \phi} = 0. \tag{2.9}$$

Substituting (2.7) into (2.8) and (2.9), we have

$$\frac{d}{dr}\ \frac{nr^2\theta'}{s'} = s'\ \frac{\partial n}{\partial \theta} + \frac{nr^2 \sin\theta\cos\theta\ \phi'^2}{s'} \tag{2.10}$$

$$\frac{d}{dr}\ \frac{nr^2\sin^2\theta\phi'}{s'} = s'\ \frac{\partial n}{\partial \phi} \tag{2.11}$$

with

$$s' = \frac{ds}{dr} \geq 1. \tag{2.12}$$

With (2.12) and the chain rule, these equations can be written as

$$\frac{d}{ds}\ (nr^2\ \frac{d\theta}{ds}) = \frac{\partial n}{\partial \theta} + nr^2 \sin\theta\cos\theta(\frac{d\phi}{ds})^2 \tag{2.13}$$

$$\frac{d}{ds}\ (nr^2\sin^2\theta\ \frac{d\phi}{ds}) = \frac{\partial n}{\partial \phi}\ . \tag{2.14}$$

These two equations should be sufficient to determine the ray trajectory. The corresponding Euler equation for r can be derived from (2.13) and (2.14) using the constraint (2.4).

2.3 The Spherically Symmetric Case

For the case where the refractive index depends only upon r, (2.13) and (2.14) become

$$\frac{d}{ds}\left(nr^2 \frac{d\theta}{ds}\right) = nr^2 \sin\theta\cos\theta\left(\frac{d\phi}{ds}\right)^2 \qquad (2.15)$$

$$\frac{d}{ds}\left(nr^2 \sin^2\theta \frac{d\phi}{ds}\right) = 0. \qquad (2.16)$$

Integrating (2.16), we have

$$nr^2 \sin^2\theta \frac{d\phi}{ds} = C_1. \qquad (2.17)$$

We may choose the coordinate system so that $\frac{d\phi}{ds} = 0$ initially. Then, $C_1 = 0$ and (2.17) yields

$$\frac{d\phi}{ds} = 0$$

for all s. This reduces the problem into a two dimensional problem, that is

$$\frac{d}{ds}\left(nr^2 \frac{d\theta}{ds}\right) = 0. \qquad (2.18)$$

This result will be used in the following sections to calculate the error of angular measurement due to refraction in an atmosphere when spherical coordinates are specified and the refractive index of the atmosphere is given.

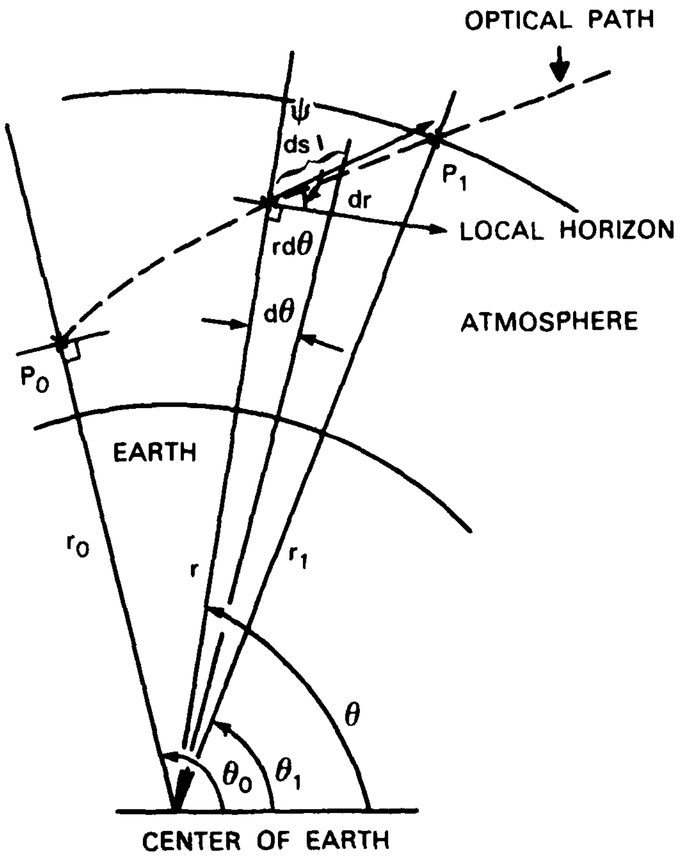
III. ELEVATION REFRACTION ERROR FOR SENSOR VIEWING THROUGH ATMOSPHERE

In this section, we will limit ourselves to describing the gross characteristics of atmospheric refraction. Other causes of refraction such as irregularities and variations within the earth's atmosphere which can not be determined by theory will not be considered. Furthermore, we assume the refractive index of the earth's atmosphere is spherically symmetric and depends only upon r, the distance to the center of the earth. The non-sphericity of the earth can be taken into account locally while applying results of this section by using the effective earth radius at a given latitude and the associated model atmosphere.

Let us consider a light ray passing through P_0 and P_1 in the earth's atmosphere as shown in Figure 3.1. Due to the spherically symmetric assumption, the trajectory of the light ray lies in a two dimensional plane and can be represented in polar coordinate as shown in Figure 3.1. Furthermore, the trajectory, $s(r,\theta)$, satisfies (2.18), or equivalently,

$$nr^2 \frac{d\theta}{ds} = \text{constant}. \tag{3.1}$$

Let us define the ray inclination angle, ψ, to be the angle between the tangential vector of the ray and the



$$r \frac{d\theta}{ds} = \cos \psi$$

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Fig. 3.1 The trajectory of a light ray lies in a two dimensional plane.

local horizon. Then, (3.1) becomes

$$n\ r \cos \psi = C_0 \qquad (3.2)$$

where C_0 is determined from the initial values of n, r and ψ at P_0, that is

$$n\ r \cos \psi = n_0\ r_0 \cos \psi_0. \qquad (3.3)$$

If the refractive index were constant between P_0 and P_1, (for example, the atmosphere removed), (3.3) reduces to

$$r_1 \cos \psi_1 = r_0 \cos \psi_0. \qquad (3.4)$$

The equality holds when the ray is a straight line. The angle, $\psi_0 (=\psi_1)$ is commonly called the elevation angle of an object at P_1 with respect to an observer at P_0. The range, R, is defined as the distance between P_0 and P_1.

As demonstrated in Figure 3.2, an object at P_1 $(r=r_1)$ with a range R from P_0 would be observed to have an apparent elevation angle ψ_0 at P_0, as if it were seen at P_1^* with a range R from P_0. If no atmosphere were present, the true elevation angle would be α as indicated in Figure 3.2. The elevation error due to refraction is defined as

$$\Delta\alpha = \psi_0 - \alpha. \qquad (3.5)$$

Let ψ_1 be the angle between the tangential vector of the ray at P_1 and the local horizon as shown in Figure 3.2. Then, we have

$$\alpha = \psi_1 - \beta \qquad (3.6)$$

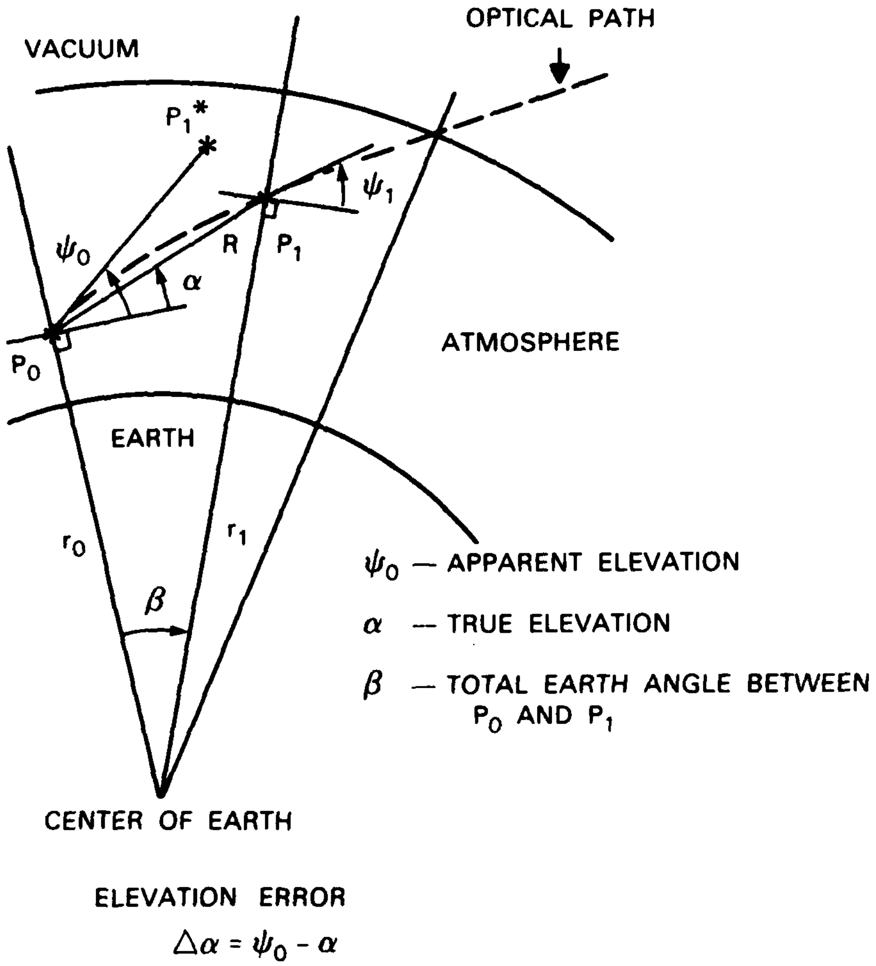

Fig. 3.2 The elevation error due to refraction when the target is at a range R.

where

$$\psi_1 = \cos^{-1}\left(\frac{C_0}{n_1\ r_1}\right) \qquad (3.7)$$

and

$$\beta = \int_{r_0}^{r_1} d\theta\ , \qquad (3.8)$$

with $C_0 = n_0\ r_0 \cos\psi_0$ and n_0, n_1 are refractive indexes at r_0 and r_1, respectively.

Using the fact that $\sin\psi = \frac{dr}{ds}$, (3.1) can be rewritten in the form

$$nr^2 \sin\psi\ \frac{d\theta}{dr} = C_0 . \qquad (3.9)$$

Substituting (3.9) into (3.8) and $\sin\psi$ by a function of $\cos\psi$, and using (3.2), we obtain

$$\beta = \int_{r_0}^{r_1} \frac{C_0\ dr}{nr^2\sqrt{1-(C_0/nr)^2}} \qquad (3.10)$$

Notice that the refractive index n is a function of r. There is no closed form expression of this integral in general. Whenever the function n is specified, β can be determined by numerical integration for a given ψ_0.

For a given set of parameters (α, R, r_0), $\Delta\alpha$ is determined by solving ψ_0 such that

$$r_1 \sin\beta = R \cos\alpha \tag{3.11}$$

where β is a function of ψ_0 as given by (3.10) and $r_1 = \sqrt{R^2 + r_0^2 + 2Rr_0 \sin\alpha}$.

For the case when $n = n_0$ over $[r_0, r_1]$, we have

$$\beta = \cos^{-1}(C_0/n_0 r_1) - \cos^{-1}(C_0/n_0 r_0) \tag{3.12}$$

or

$$\beta = \psi_1 - \psi_0. \tag{3.13}$$

It is easy to see that $\Delta\alpha = 0$ and (3.11) is satisfied.

IV. REFRACTIVE INDEX OF AIR

As mentioned in Section I, the refractive index, n, of a medium for a light ray is defined as

$$n = v/c \tag{4.1}$$

where c is the velocity of the light propagating in vacuum while v is the velocity in the medium. The velocity of a light ray propagating through the atmosphere varies with changes in atmospheric composition, pressure, and temperature. It is strongly wavelength dependent at optical wavelengths, but it is not affected appreciably by water vapor. In this report, we adopt a simplified version of Edlen's expression for the refractive index of air[4] as follows:

$$n \approx 1 + 10^{-6} \times (77.46 + 0.459/\lambda^2) \frac{P}{T} \tag{4.2}$$

where λ = wavelength in micrometers (μm)
P = atmospheric pressure in millibars
T = atmospheric temperature in degrees Kelvin.

The atmospheric temperature and pressure variations are principally functions of altitude, season and latitude.

4.1 Model Atmospheres

Six model atmospheres used in LOWTRAN 5[3] (a computer code for atmospheric transmittance and radiance computa-

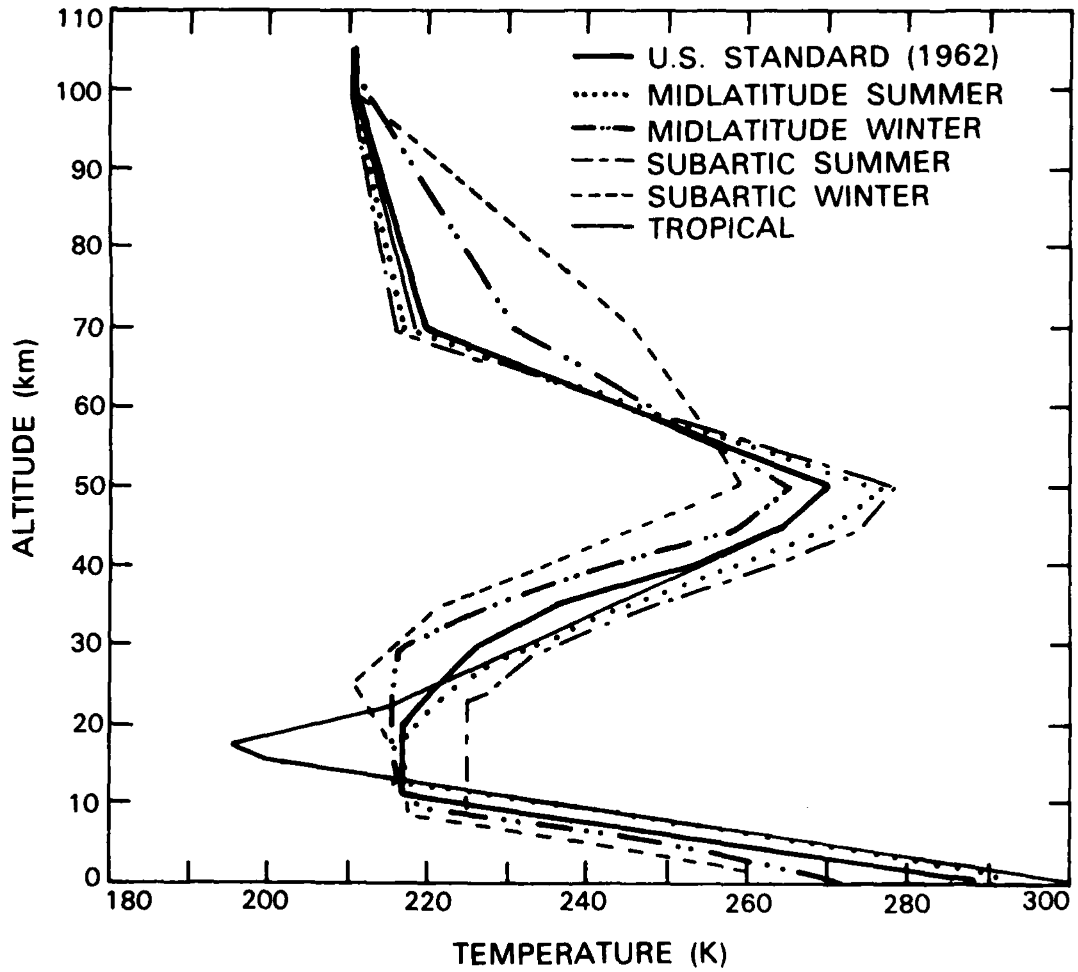

Fig. 4.1 The temperature profiles as a function of altitude.

tion) are considered in this report. The model atmospheres correspond to the 1962 U.S. standard atmosphere and five supplementary models; that is, Tropical (15°N), Midlatitude Summer (45°N, July), Midlatitutde Winter (45°N, January), Subarctic Summer (60°N, July), and Subarctic Winter (60°N, January). The different models are digitized in 1-km steps from 0 to 25 km, 5-km steps from 25 to 50 km, then at 70 km and 100 km directly as given by McClatchey et.al.,[5].

The temperature profiles for these models as a function of altitude are shown in Figure 4.1. The pressure profiles are given in Figure 4.2. Figure 4.3 shows the profiles of pressure to temperature ratio for these models. Notice that the 1962 U.S. standard model has a pressure to temperature ratio profile very close to the mean of these profiles. The refractive modulus

$$N = (n-1) \times 10^6 \qquad (4.3)$$

which is proportional to the pressure-to-temperature ratio according to Equation (4.2), is also given in Figure 4.3 at $\lambda = 11\mu m$.

In the next subsection, we will describe the scheme of calculating the refraction error for an object at a given range and elevation angle. Sensitivities of refraction errors to the object range, atmospheric model mismatch will be presented.

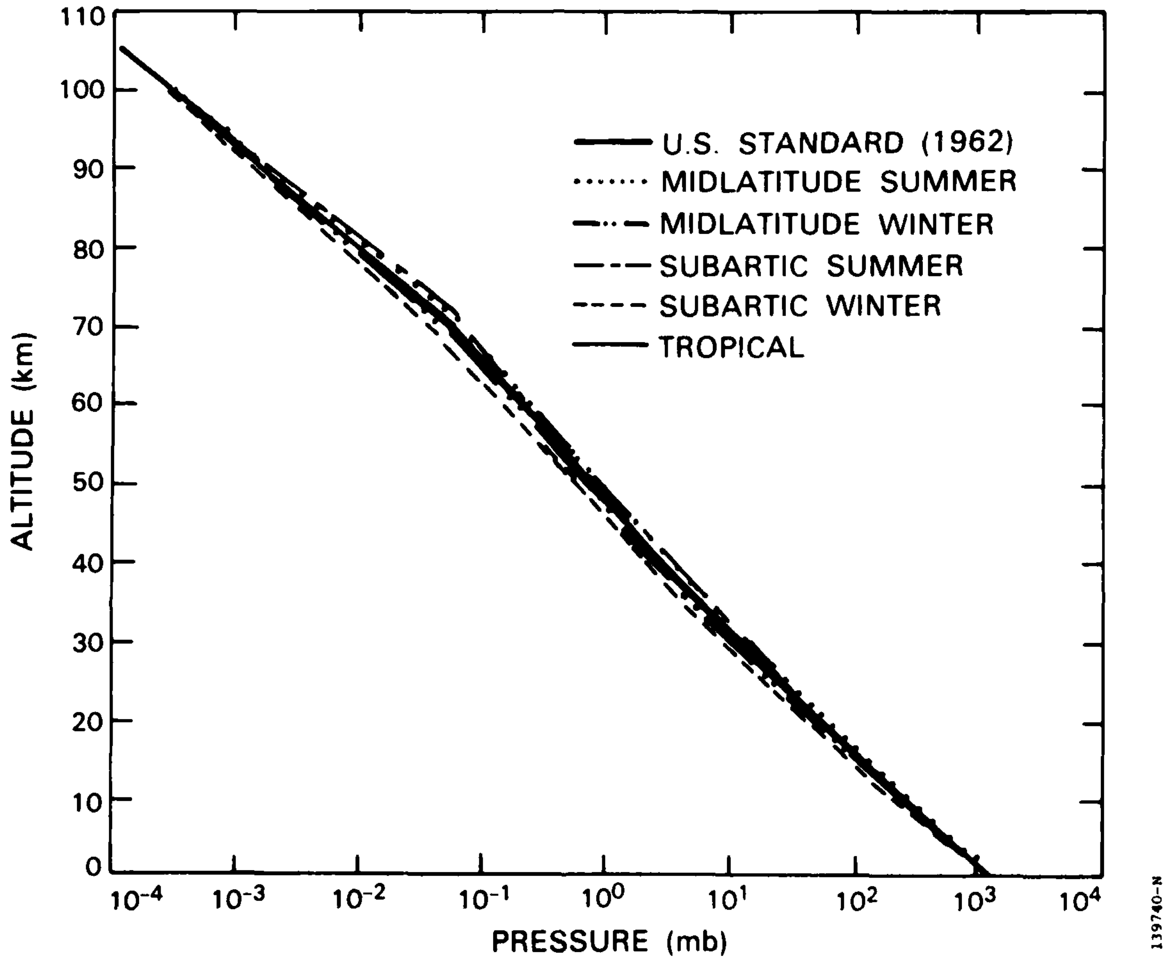

Fig. 4.2 The pressure profiles as a function of altitude.

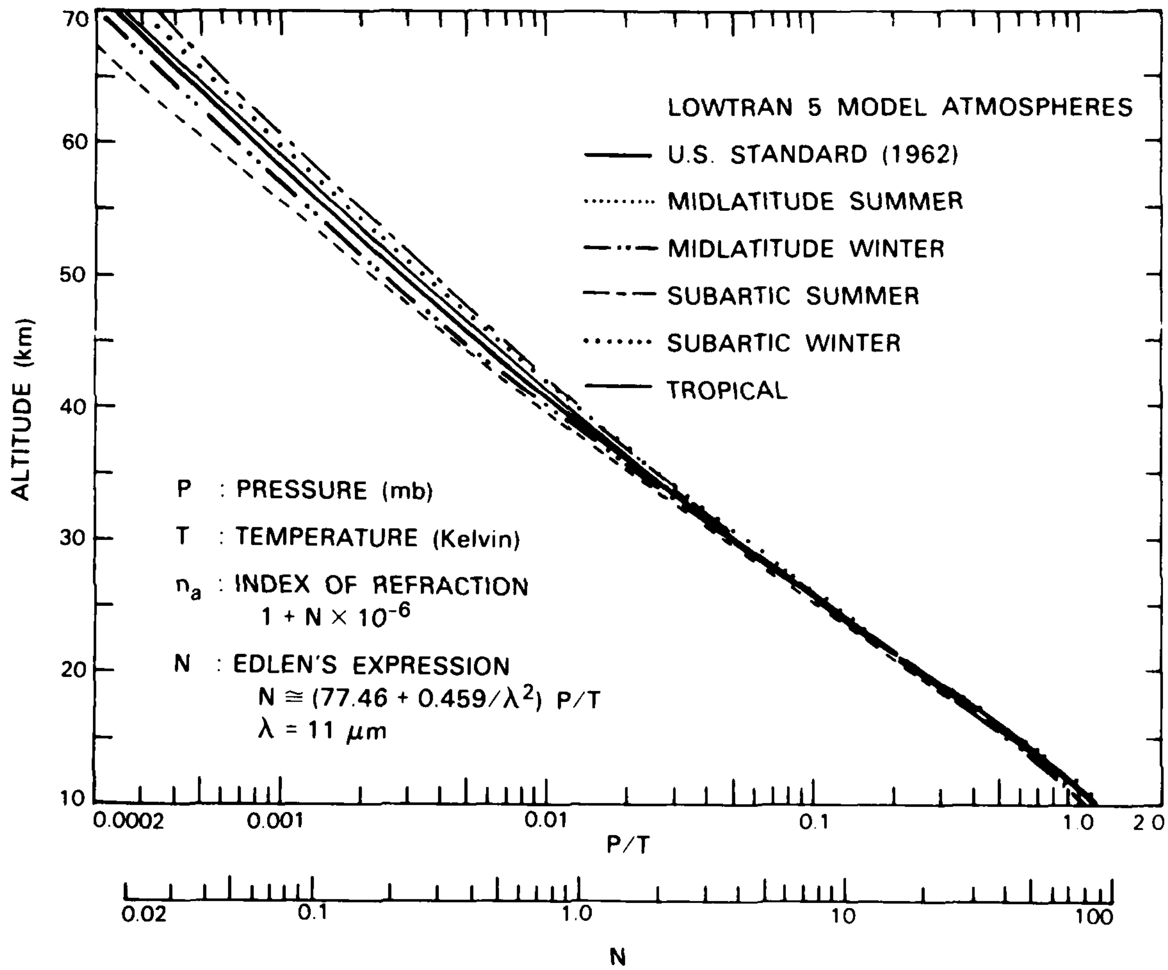

Fig. 4.3 The profiles of pressure to temperature ratio as a function of altitude.

4.2 Elevation Refraction Error Computation For A Given Atmospheric Model

In this subsection, we apply the refraction equations and various atmospheric models to show how well the true target elevation can be estimated from the apparent target elevation and approximate knowledge of the target range and atmospheric parameters.

Let us assume that the refractive index of a given atmospheric model for a light ray of wavelength λ_0 can be expressed by the following piecewise constant function

$$n(h) = n_i \qquad \text{for } h_{i-1} \leq h < h_i \tag{4.4}$$

where h is altitude in km and h_i's are altitude steps defined in the LOWTRAN 5 code. Substituting (4.4) into (3.10), we have

$$\beta = \cos^{-1}[C_0/n_{M+1}(R_e+h_T)] - \cos^{-1}[C_0/n_{M+1}(R_e+h_M)]$$

$$+ \sum_{i=L}^{M-1} \left\{\cos^{-1}[C_0/n_{i+1}(R_e+h_{i+1})] - \cos^{-1}[C_0/n_{i+1}(R_e+h_i)]\right\} \tag{4.5}$$

$$+ \cos^{-1}[C_0/n_L(R_e+h_L)] - \psi_0$$

where

$$C_0 = n_L(R_e+h_s)\cos\psi_0 \tag{4.6}$$

R_e is the earth radius and h_s, h_T are the sensor and target altitudes, respectively. The indices L and M are determined by h_S and h_T as below:

$$\begin{aligned} h_{L-1} &\leq h_s < h_L \\ h_M &\leq h_T < h_{M+1} . \end{aligned} \tag{4.7}$$

For a given set of parameters (α, R, h_s), an iterative scheme has been used to solve for ψ_0 such that (3.11) is satisfied, that is

$$(R_e + h_T)\sin\beta = R\cos\alpha \tag{4.8}$$

where β is a function of ψ_0 as given in (4.8) and h_T is obtained by the following relation:

$$h_T = [(R_e+h_s)^2 + R^2 + 2R(R_e+h_s)\sin\alpha]^{1/2} - R_e . \tag{4.9}$$

As illustrated in Figure 4.4, the iterative scheme used in this report is described as follows:

1. For a given set of parameters (α, R, h_s), determine h_T, L and M according to Equations (4.9) and (4.7), respectively. Let $\psi_0 = \alpha$ and $j = 1$.

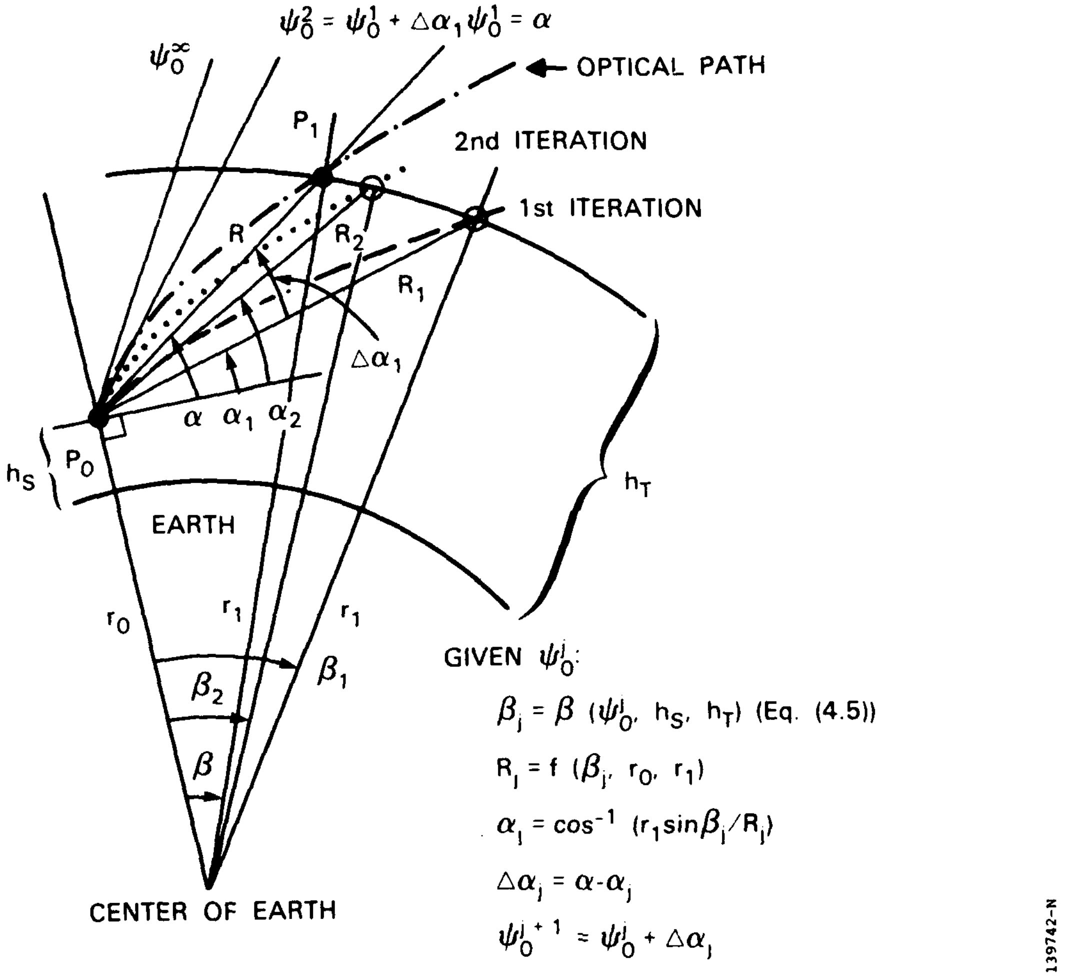

Fig. 4.4 The iterative scheme used to calculate the elevation error, when (α, R, h_S) is given.

2. Compute β_j by (4.5) for the given ψ_0.

3. A new target range is computed as

$$R_j = [(R_e+h_s)^2 + (R_e+h_T)^2 - 2(R_e+h_s)(R_e+h_T)\cos\beta_j]^{1/2}$$

and the associated elevation angle as

$$\alpha_j = \cos^{-1}[(R_e+h_T)\sin\beta_j/R_j].$$

The difference of α and α_j is

$$\Delta\alpha_j = \alpha - \alpha_j.$$

4. If

$$|\Delta\alpha_j| \leq \varepsilon \text{ (tolerance limit of the algorithm).} \quad (4.10)$$

go to step 5. Otherwise set

$$j = j + 1$$

$$\psi_0 = \psi_0 + \Delta\alpha_j$$

and go to step 2.

5. The elevation error due to refraction is computed as

$$\Delta\alpha = \psi_0 - \alpha$$

and the iteration procedure stops.

Figure 4.5 shows uncompensated elevation errors due to refraction in μ radians as a function of the actual object elevation angle with different ranges (from 500 km to ∞) from a sensor at an altitude of 15 km. The atmospheric model used here is the 1962 U.S. standard atmosphere provided by LOWTRAN 5. In the case where the range information of the target is

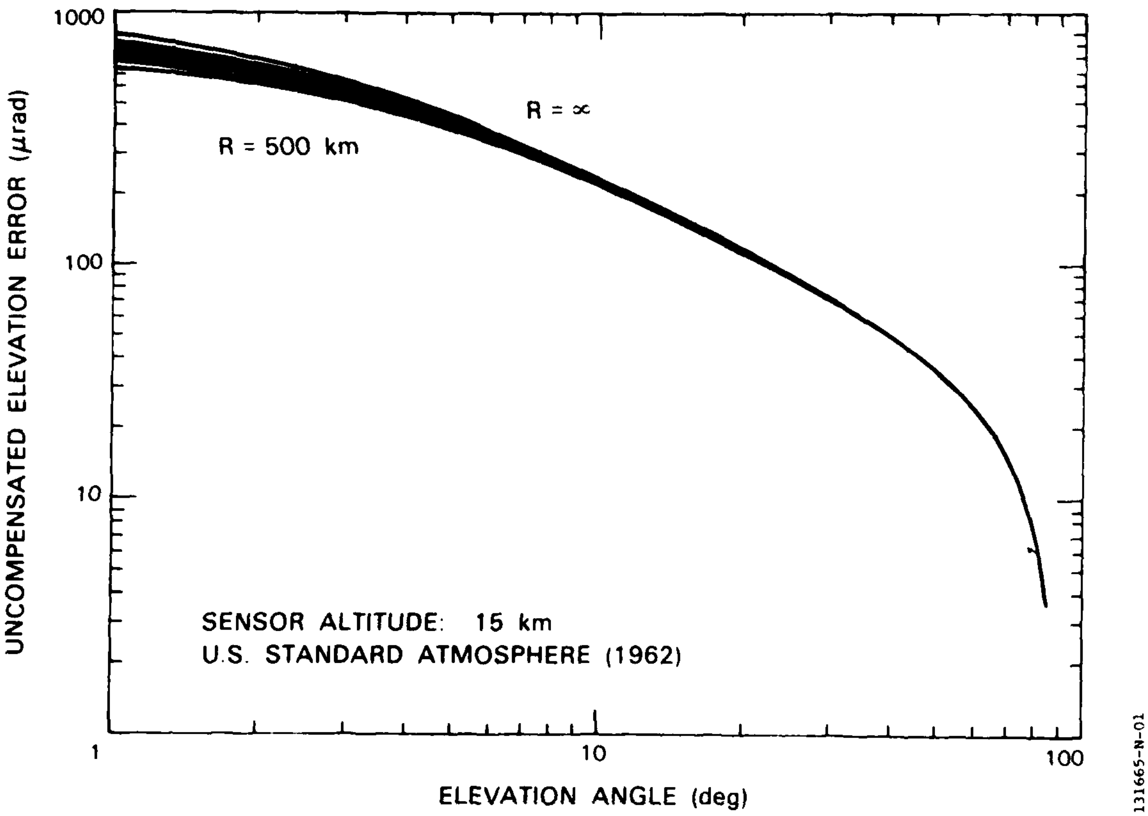

Fig. 4.5 The uncompensated elevation errors due to atmospheric refraction.

not available, the elevation angle is compensated for a <u>preset</u> range, say 1000 km in the example shown in Figure 4.6. Bias errors for targets at ranges of 500, 1000 and ∞ km are shown in Figure 4.6 for the sensor presented in Figure 4.5. For other atmospheric models, bias errors due to mismatched range follow similar trends and magnitudes as those with the 1962 U.S. standard profile; they are shown in Figure 4.7. For a mismatched atmospheric profile, Figure 4.8 shows bias errors for objects at a common range of 1000 km for all atmospheric models which are compensated by the 1962 U.S. standard profile with the true range. The maximum refraction bias that includes range and model mismatches is presented in Figure 4.9 with thereference model and range indicated. This figure presents a spread of elevation biases over a wide range of atmospheric mismatches. For actual applications, the atmospheric profile is known to a certain accuracy. Mismatches presented in Figure 4.9 will only occur in a few extreme cases. A statistical model of the atmospheric profile should be used to evaluate the elevation errors in a statistical sense.

4.3 A Statistical Model For Atmospheric Uncertainties

It would be very complicated to express atmospheric temperature and pressure variations with a statistical model. To evaluate the elevation bias due to refraction, we only need

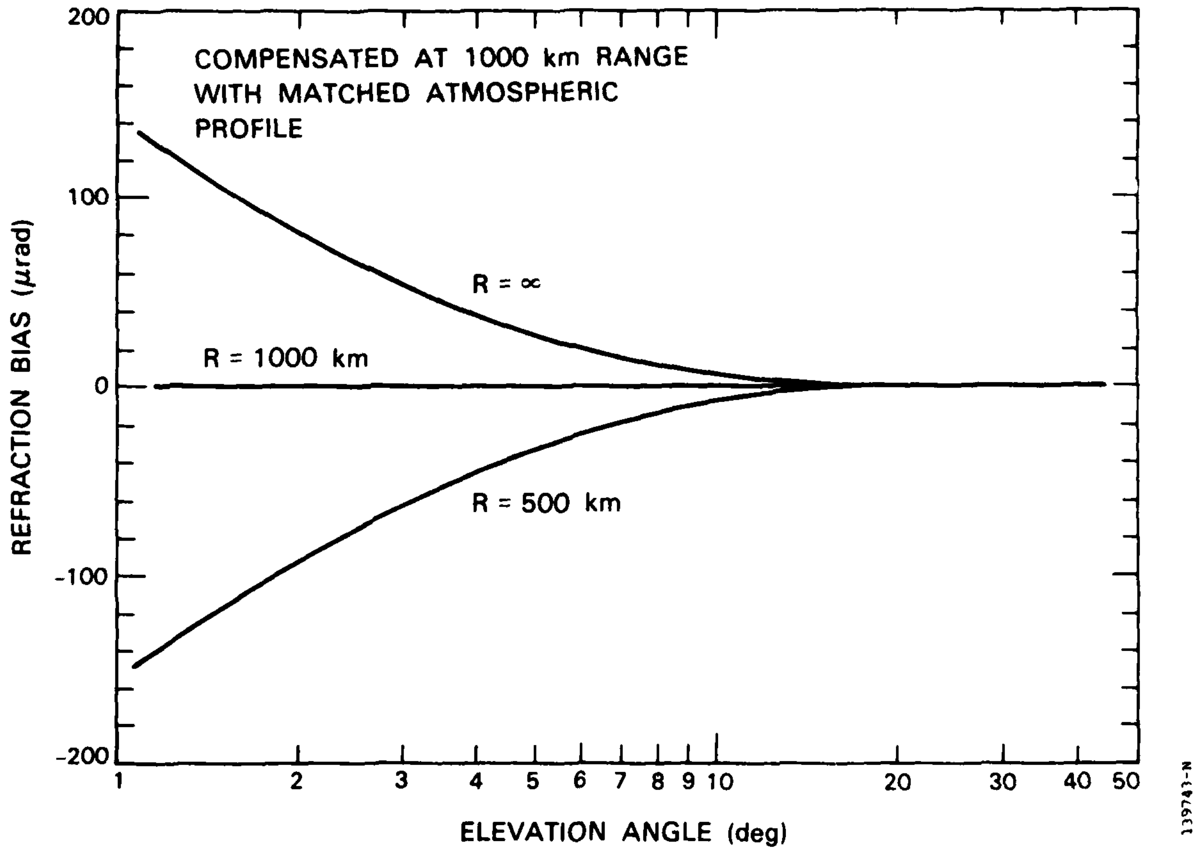

Fig. 4.6 The bias errors for targets at range indicated when the elevation angle is compensated for a preset range.

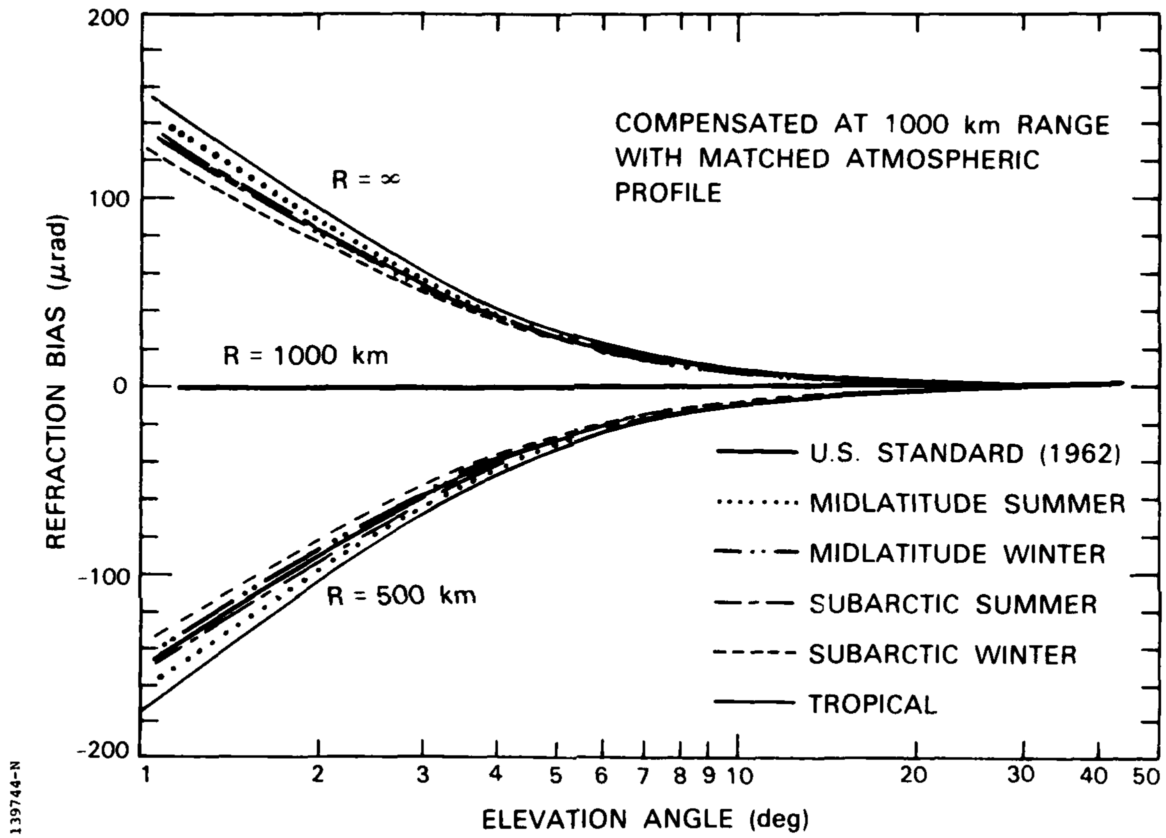

Fig. 4.7 The bias errors due to mismatched range setting in the compensation for different atmospheric models.

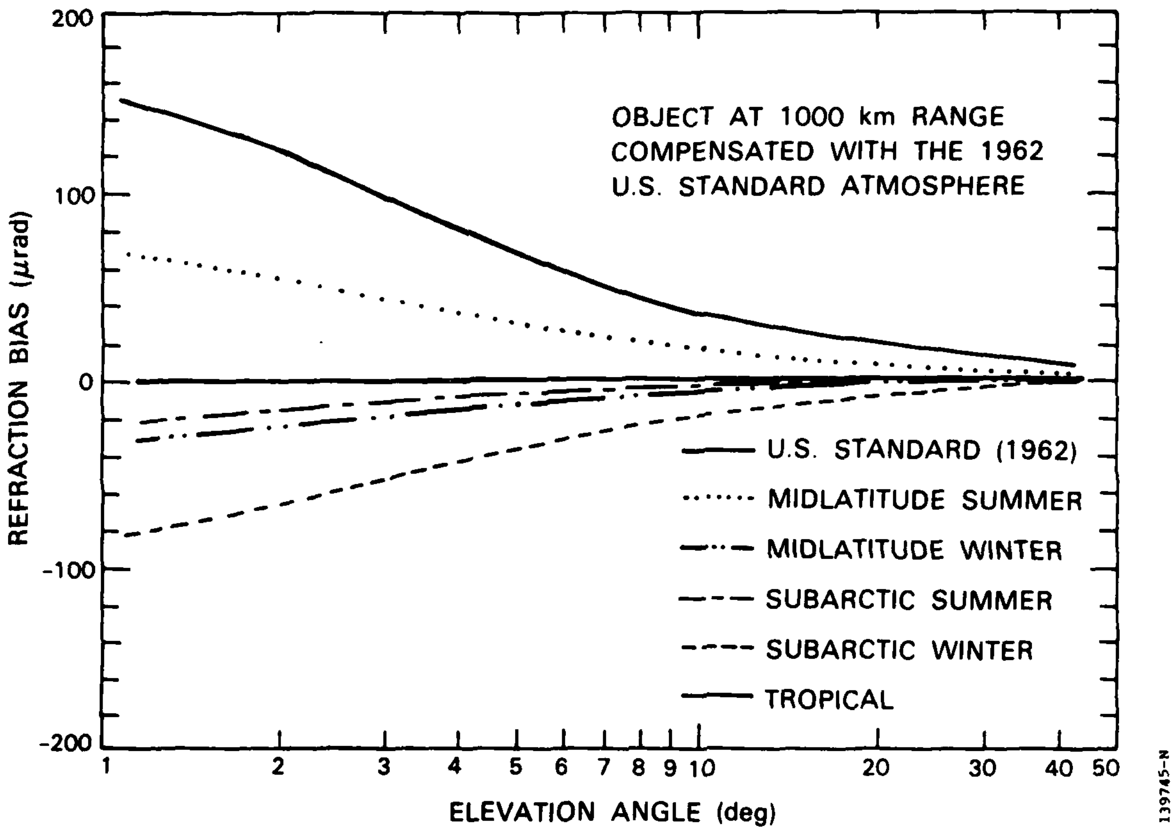

Fig. 4.8 The bias errors due to mismatched atmospheric model in the compensation for a matched range setting.

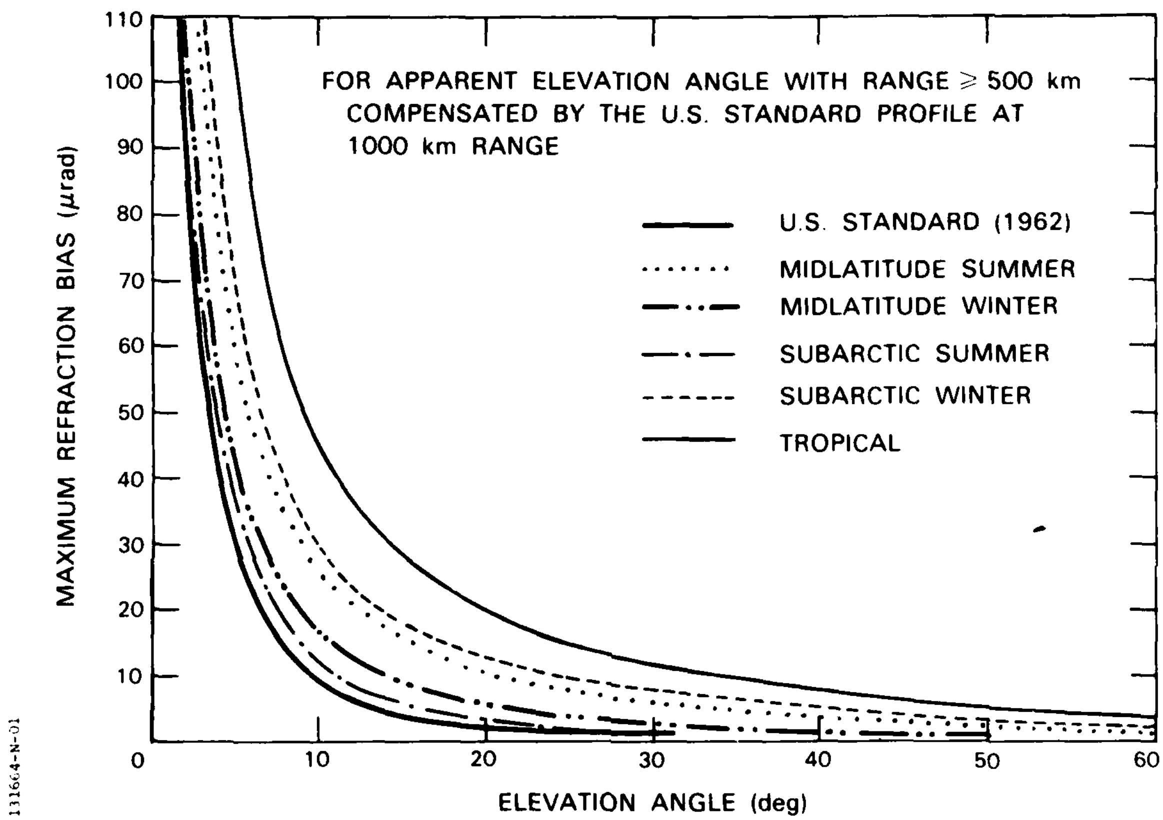

Fig. 4.9 The maximum refraction bias that includes the range and reference model mismatches.

to know the pressure to temperature ratio. It is much simpler to model the fluctuations of this ratio. As we have seen in Figure 4.3, the variations of this ratio are very small for a wide range of atmospheric models. As mentioned previously, the 1962 U.S. standard atmosphere model has a pressure to temperature ratio very close to the mean of the six atmospheric models considered. In this report, we construct a statistical model of the pressure to temperature ratio for an atmosphere which has mean profile identical to the 1962 U.S. Standard profile as follows:

$$(P/T)_i = (P/T)_{i+1} - (z_{i+1}-z_i)(\Delta_z(P/T)_i + \sigma_i \upsilon_i); \qquad i=1,2,..,34$$

$$(P/T)_{34} = 0, \tag{4.11}$$

where

$$\Delta_z(P/T)_i = (P_{i+1}/T_{i+1} - P_i/T_i)/(z_{i+1}-z_i)$$

P_i = Atmospheric pressure in millibars of the 1962 U. S. Standard atmosphere at altitude z_i

T_i = Atmospheric temperature in degrees Kelvin of the 1962 U.S. Standard atmosphere at altitude z_i

σ_i = Standard deviation of $\Delta_z(P/T)_i$ which is a half of the sample standard deviation of the six atmospheric models provided by LOWTRAN 5 at altitude z_i

υ_i = A random normal distributed number with mean zero and unit standard deviation.

Figure 4.10 and 4.11 show the mean and standard deviation of 50 Monte Carlo runs of elevation errors after compensation. The same conditions are assumed here as those in Figures 4.6 - 4.9. It is interesting to note that the mean error is very close to the bias presented in Fig. 4.6 for the deterministic case The standard deviation is less than 200 μrad at 1° elevation angle for the worst case.

4.4 Geometric Considerations

From the results presented in this section, it is seen that refraction errors become much more significant at low elevation angles. The elevation angle is a function of target and sensor altitudes and the distance between them as shown in Figure 4.12.

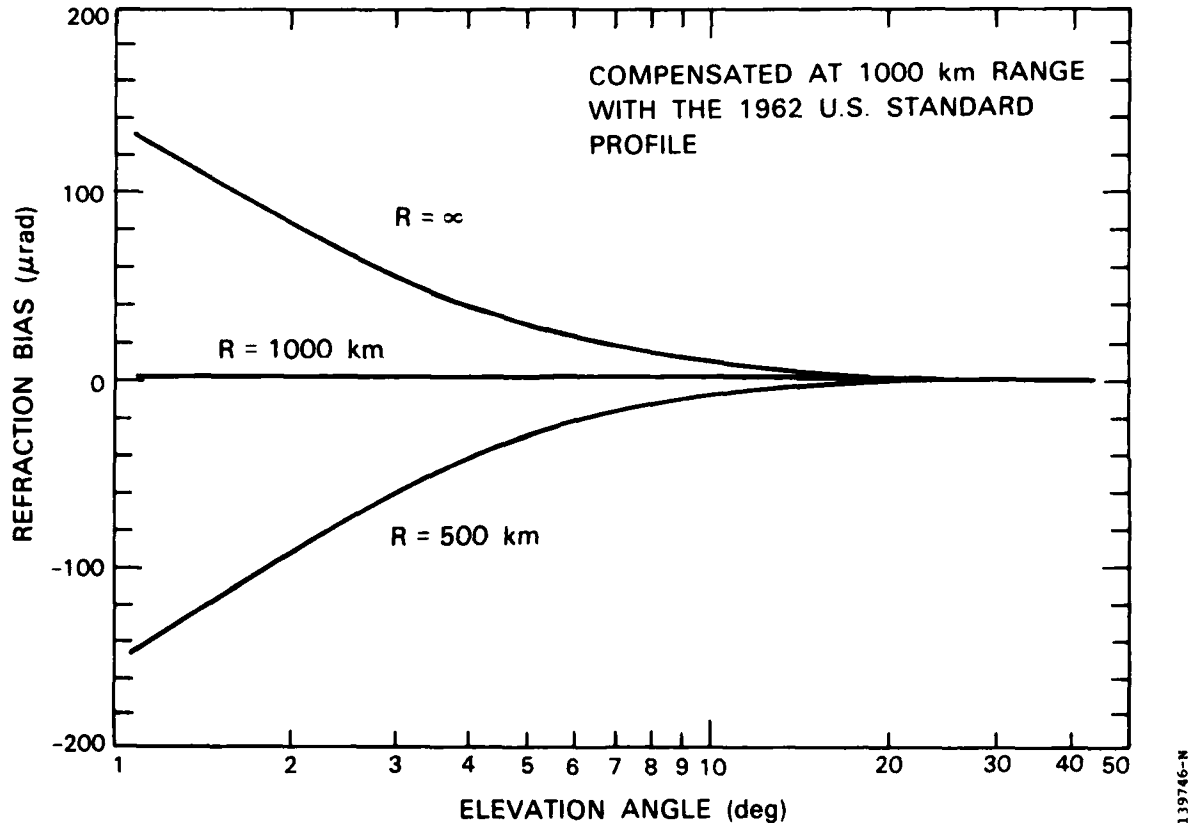

Fig. 4.10 The mean of elevation errors after compensation for a statistical atmosphere model.

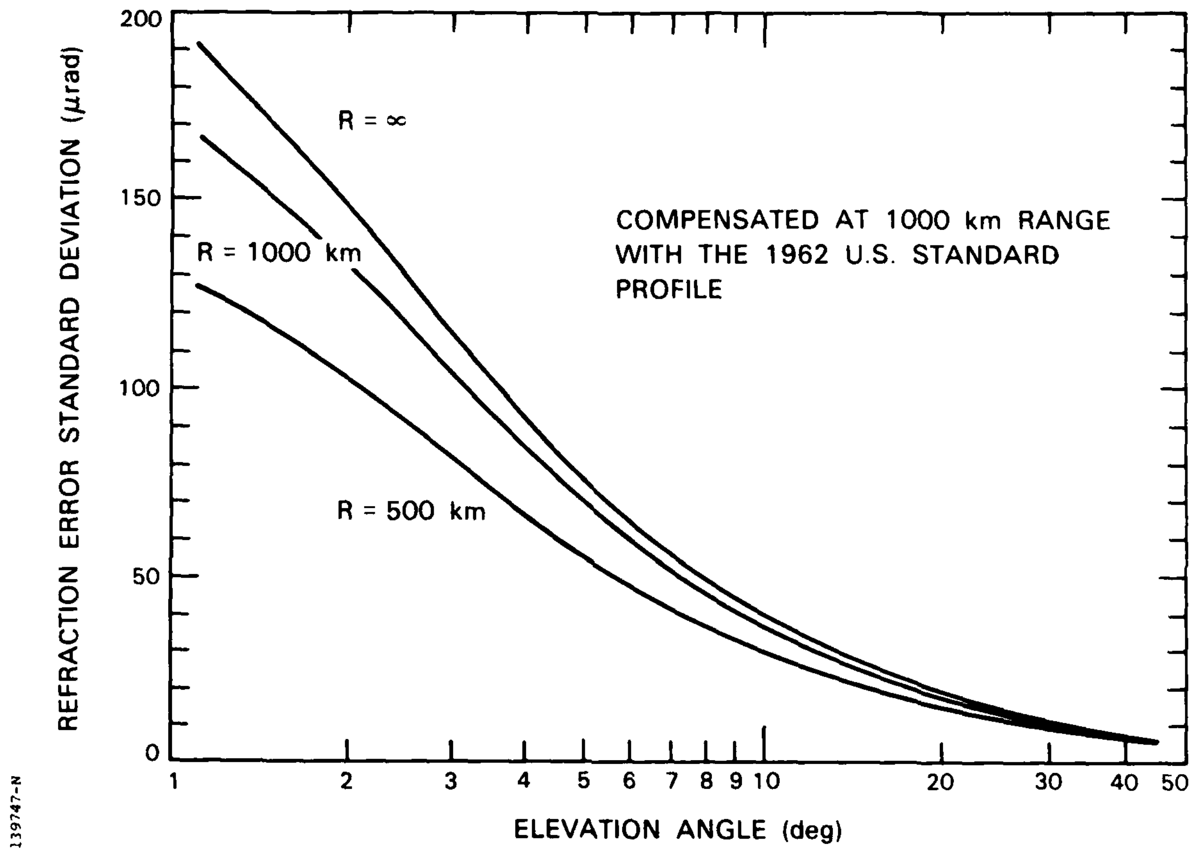

Fig. 4.11 The standard deviation of elevation errors after compensation for a statistical atmosphere model.

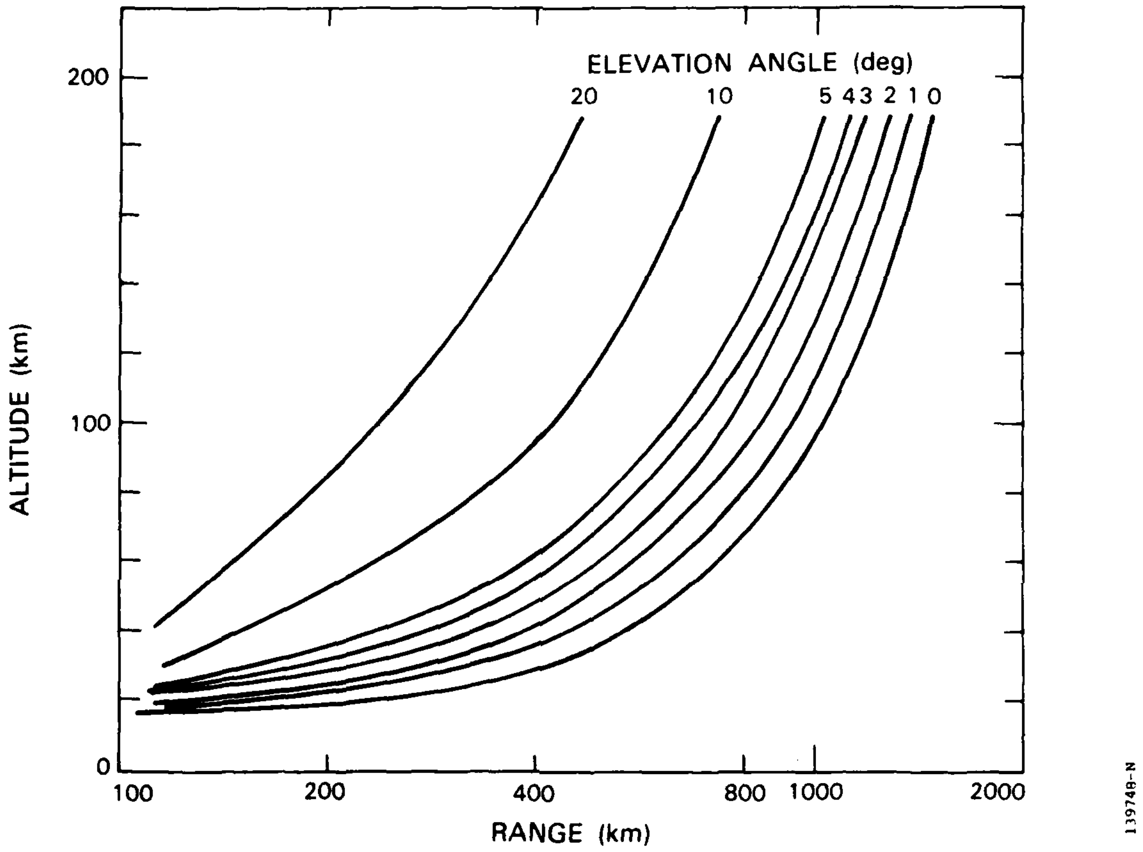

Fig. 4.12 The elevation angle of target as a function of target altitude and range to a sensor at 15 km altitude.

V. SUMMARY AND CONCLUSIONS

A formula which can be used to compute the refraction error of an object at a finite range in a given atmosphere is derived. An algorithm which obtains an approximate solution of the formula is presented. Sensitivities of the bias error to the range and/or atmospheric model used in the compensation scheme are also presented. A statistical model which simulates the effects of the refraction errors due to fluctuations in the atmospheric temperature and pressure is presented. Simulation results are presented. From various sensitivity studies presented here, it is important to conclude that the most important portion of the bias error is due to the range mismatch. The bias error can be minimized by carefully selecting a reference range within the operational range of the sensor.

A major conclusion from the results presented above is that refraction errors are most serious at low elevation angles.

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